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Hydrologic Risk and Return Period Selection for Water-Related Projects

By
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TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

FOREWORD

This Technical Note provides guidance to hydrologists and engineers (and other specialists involved with water projects) faced with the task of determining a design hydrologic event for a project that involves hydrologic risk. Such projects may include bridges, culverts, land treatments, dams, fish habitat improvements, watershed management projects, etc. Included is a discussion of hydrologic risk that defines both the manager's and specialist's roles in determining risk levels for BLM-funded projects. An extensive section on frequency of hydrologic events is included for the specialist, followed by a section on guidelines and graphical aids for determining return periods. The latter section includes problem-oriented examples of return period selection.

Event frequency analysis, including confidence limits on frequency curves, is briefly discussed.

INTRODUCTION

Hydrologists and engineers are frequently asked to provide design flows or stages for spillways, bridge openings, culverts, diversion dams, waterways, fish improvement structures, watershed improvement projects, and land treatment measures. Too often, a return period or recurrence interval is arbitrarily chosen or a standard return period is used by the specialist.

The design event chosen by the specialist should be based on the risk of failure rather than on an arbitrary or predetermined return period, incorporating the fact that risk increases with increasing project life.

Since failure of a structure exposes the Federal government to potential liability claims, the acceptance of a certain level of risk of failure represents an important management decision.

The purpose of this Technical Note is to assist the specialist in understanding hydrologic risk and in communicating this understanding to the land manager. With the statistical relationships and graphs included, this Technical Note can also serve as a reference for the hydrologist and other specialists involved with water-related projects where the frequency of hydrologic events is a concern.

ACCEPTANCE OF HYDROLOGIC RISK AS A MANAGEMENT RESPONSIBILITY

In water-related projects or structures, risk is equivalent to the probability of failure of the structure. The total risk of failure is made up of both hydrologic risk and structural risk. Structural risk refers to the probability that a structure will fail during an event of lower magnitude than the design event. Hydrologic risk consists of (1) true or inherent risk and (2) data uncertainty. These are two very different concepts and are treated by separate statistical routines. The inherent risk is a function of the randomness of natural climatic and hydrologic events. For example, the 100-year flood refers to the average probability of occurrence (or exceedance) of a flood of certain magnitude. It is a concept based on mathematical theory. Data uncertainty, on the other hand, results from errors in water data collection, from external (nonrandom) influences on hydrologic variables, or from the lack of goodness-of-fit of a frequency distribution fitted to a hydrologic data series. External factors that could affect the randomness of (i.e., produce "nonhomogeneity" in) a data set include such things as land-use changes, wildfires, insect or disease epidemics, or other natural disasters in watersheds.

If we assume that structural risk is zero or near zero for hydrologic events not exceeding the design event, and that hydrologic uncertainty can be handled with confidence limits in the frequency analysis, then the remaining unknown variable is basic hydrologic risk. For large projects, the manager may want to conduct an elaborate study of the economically and politically optimum design for the project. This can be done as shown in Figure 1. The construction costs include the total cost of building the structure averaged over the expected project life plus annual maintenance costs. The risk costs include all those costs that would be incurred should the project or structure fail. For projects that impound water, these costs should include project replacement costs, downstream damage costs, liabilities from deaths and injuries, environmental damages, and the associated inconveniences and political consequences of project failure. The optimum design, from Figure 1, is where the construction cost balances the risk cost.

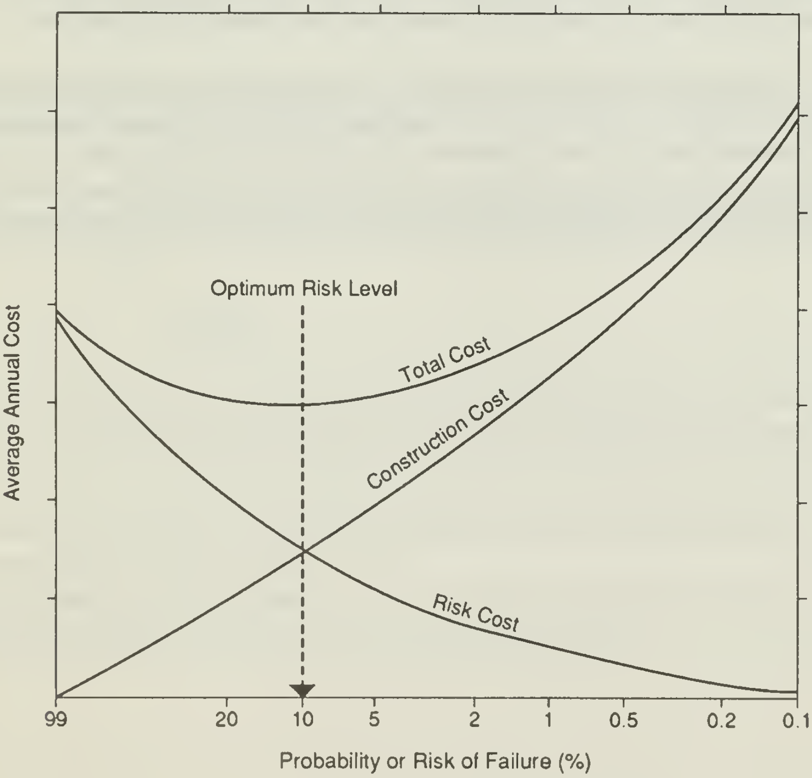

Figure 1. Average Annual Costs for Different Project Designs

For small projects, the manager must still weigh the cost of constructing the project against the risk cost and attempt to minimize both. For example, constructing a stream stabilization structure to withstand a 50-year flood event is more expensive than designing it for a 10-year flood event. However, the environmental consequences of the structure failing at the 10-year design level (approximately five times more frequently) may dictate designing for the 50-year flood. On the other hand, where the costs of failure are negligible, as in a secondary road culvert, the manager can easily accept a much higher risk, on the order of 10 to 20 percent. Acceptance of a given hydrologic risk, say 5 percent, means the manager is 95 percent confident that the associated hydrologic event will not be equaled or exceeded in the stated time period and that the structure or project will not fail for hydrologic reasons.

Many laymen and occasionally some hydrologists become confused about the real meaning of storm or flood return periods. For example, the commonly referred to 50-year storm does not mean that that there will be one and only one such storm every 50 years. In fact, there is only a 37 percent chance that the 50-year storm will be equaled or exceeded only once in any 50-year period. There is a nearly equal (36 percent) chance of experiencing no such storms in the same period. Furthermore. there is a 19 percent chance of experiencing exactly two such events in 50 years. Another way of interpreting the meaning of a 50-year event is to say that there is a 1/50, or 2 percent, chance of equaling or exceeding the 50-year event in any one year and, conversely, a 98 percent chance of nonoccurrence in any one year.

It must be reiterated that the probability of event occurrence increases with increasing project life. The decision on the physical life of a project is an important one and must be taken into account in selecting a design event. For example, contour trenches that have been designed to handle the 75-year storm have only a 6 percent chance of experiencing one or more equal or larger storms in the first 5 years of their life, but by the 20th year this risk has increased to 24 percent. Selecting a project life, as in determining acceptable hydrologic risk, is a management decision that relies heavily on specialist recommendations. In selecting the effective life of a project or structure, the manager must take into account the fact that risk increases with project duration. What are the objectives of the project? Do project benefits decrease over time or are they constant or cumulative with time? Can the project be discontinued (structure taken out) when project objectives are met? All the above factors should be evaluated and considered in the decision.

The respective roles of the specialist and the land manager in determining the acceptable hydrologic risk have been discussed briefly. To summarize, the land manager must ultimately decide on the level of risk that BLM will accept for any project. The specialist is responsible for ensuring that the manager understands the statistical relationships involved and the factors that determine both the risk and project life decisions. These decisions, along with the specialist's recommendations, should be well documented in the official files.

FREQUENCY OF HYDROLOGIC EVENTS IN NATURE

Several questions are often asked about the probability of occurrence of events in nature. Most common are the following: (1) What is the probability of encountering such an event in a single year? (2) What is the probability of encountering the event in a period of years? and (3) What is the probability of encountering more than one such event in a period of years? All these questions can be answered with the help of the binomial distribution:

$$f(x) = \frac{N!}{X!(N-x)!} \quad p^{x} (1-p)^{N-x} \qquad (1)$$

that is found in any standard statistical or mathematical probability text. The binomial distribution has tremendous value in hydrologic studies.

As used in hydrology, the terms return period and recurrence interval are synonymous. They are defined as the average time interval between actual occurrences of a hydrologic event of a given or greater magnitude. The reciprocal of the return period or recurrence interval is the probability of exceedance, expressed mathematically as

$$p = \frac{1}{T} \qquad (2)$$

where T, the return period, is most often expressed in years and p, the probability, is dimensionless. The probability of nonoccurrence (q) is further defined as

$$q = 1 - p = 1 - 1/T \qquad (3)$$

If T is in years, then p represents the probability of the T-year event (or a greater event) occurring in any one year.

Example: The 100-year flood has a probability of .01 or 1 percent of occurring and a probability of .99 or 99 percent of not occurring in any one year.

Now we can use the binomial distribution to give us some valuable probability information about the frequency of hydrologic events. The binomial distribution is rewritten as:

$$P = p^{i} (1-p)^{N-i} \quad \frac{N!}{i!(N-i)!} \qquad (4)$$

where P is the probability of obtaining exactly i events in N years, with i having a probability of p of occurring in any single year. Remember that an event is one that either equals or exceeds the given event. We can use Equation 4 to give some interesting probability information about the 100-year flood:

Example 1: What is the probability of experiencing only one flood in 100 years that equals or exceeds the 100-year flood?

Answer: The probability of one and only one event equal to the 100-year flood occurring in 100 years is 37 percent, or 37 chances out of a 100.

Example 2: What is the probability of experiencing no floods equal to or greater than the 100-year flood in a 100-year period?

Answer: Equation 4 reduces to

$$P = (1-p)^N \text{ or } q^N \tag{5}$$

The probability of no 100-year events occurring in 100 years is 37 percent.

We can use the complement of Equation 5 to find out the probability of experiencing one or more events equal to or greater than the 100-year event in a 100-year period, or

$$P = 1 - q^N \tag{6}$$

From Example 2, (P = 1 - .37 or p = 63 percent.)

Equation 6 was used to construct the following table of probabilities:

Table 1. Percent Probability of Occurrence of One or More Events Equal to or Greater than the T-year Event in N Years.

No. of Years (N)	Return Period (T), Years											
	5	10	20	25	50	75	100	200	500	1000	5000	10,000
5	67	41	23	18	10	6	5	2	1	*	*	*
10	89	65	40	34	18	13	10	5	2	1	*	*
20	99	88	64	56	33	24	18	10	4	2	*	*
25	**	93	72	64	40	29	22	12	5	3	*	*
50	**	**	92	87	64	49	39	22	10	5	1	*
75	**	**	98	95	78	63	53	31	14	7	1	1
100	**	**	99	98	87	74	63	39	18	10	2	1
200	**	**	**	**	98	93	87	63	33	18	4	2
500	**	**	**	**	**	**	99	92	63	39	10	5
1000	**	**	**	**	**	**	**	99	86	63	18	10
5000	**	**	**	**	**	**	**	**	**	99	63	39
10,000	**	**	**	**	**	**	**	**	**	**	86	63

*less than 1 percent **greater than 99.5 percent

Occasionally, the hydrologist may want to know the probability of experiencing multiple numbers of events equal to or greater than the return period event.

Equation 4 was used to construct the following table of probabilities related to the 100-year flood:

Table 2. Percent Probability of Occurrence of the 100-Year Flood.

No. of Years (N)	Number of Events (i)				
	0	1	2	3	1 or more
100	37	37	18	12	63
50	61	31	8	2	39
25	78	20	2	*	22
10	90	9	*	*	10
5	95	5	*	*	5
1	99	1	*	*	1

* less than 1 percent

Tables 1 and 2 can be used for any set of hydrologic data developed from discrete hydrologic variables, such as streamflow stage or discharge, lake levels, ground-water levels, precipitation, evaporation, etc.

SELECTING THE RETURN PERIOD OF A HYDROLOGIC EVENT

Given the risk level and the project life, the hydrologist can compute the return period from Equation 4 by solving for p. Since this is an unwieldy computation, three graphs have been prepared to make this determination simple. Figure 2 is used to determine the return period corresponding to the risk of experiencing one or more events equal to or greater than the return period event in N years. Figure 3 should be used where the interest is in two or more events equal to or greater than the return period event. Figure 4 is used where the interest is in three or more events equal to or greater than the return period event. Examples of the use of these graphs are shown below:

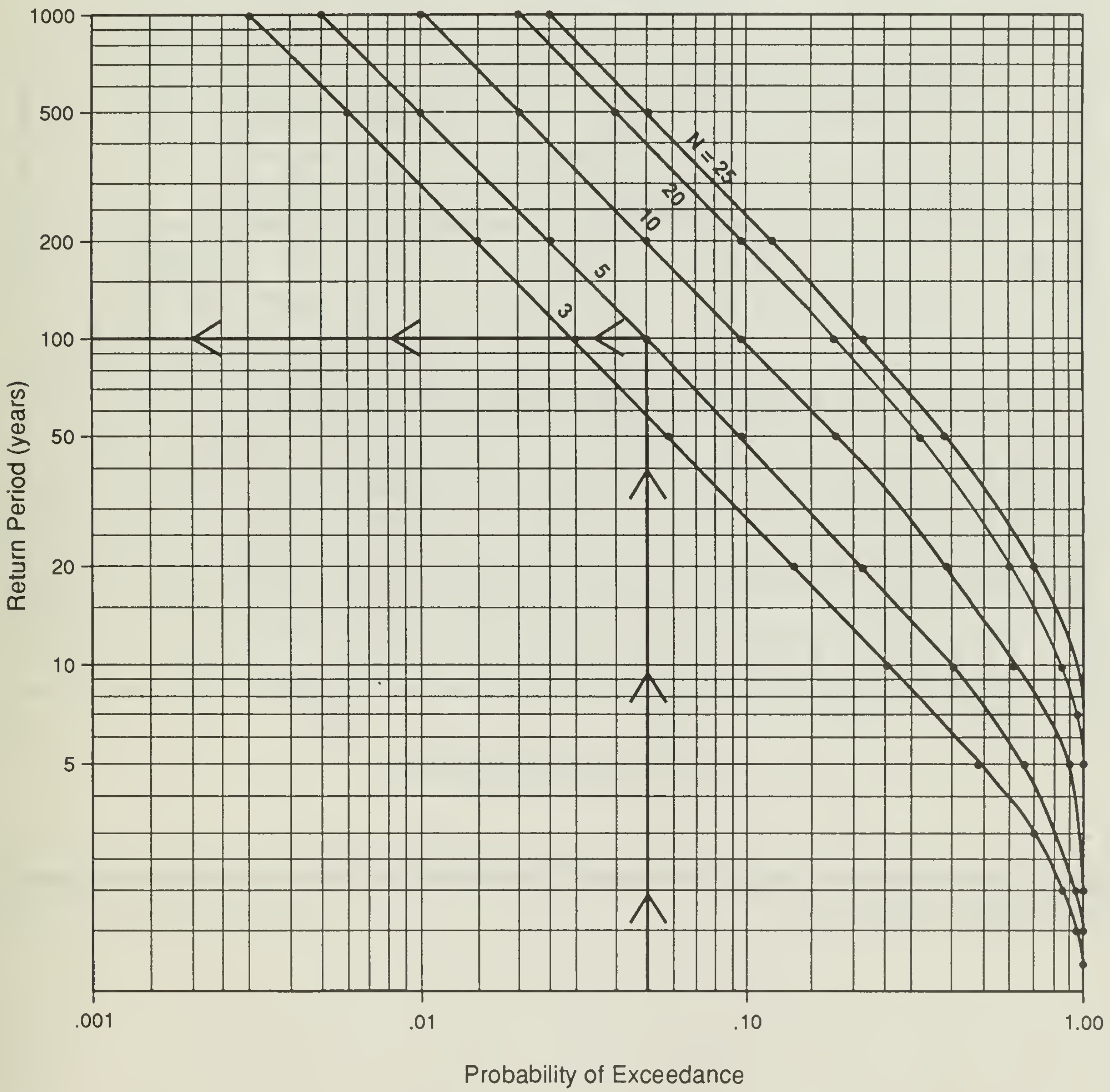

Figure 2. Return Periods Corresponding to the Probability of Experiencing One or More Events Equal to Or Greater than the T-Year Event in N Years.

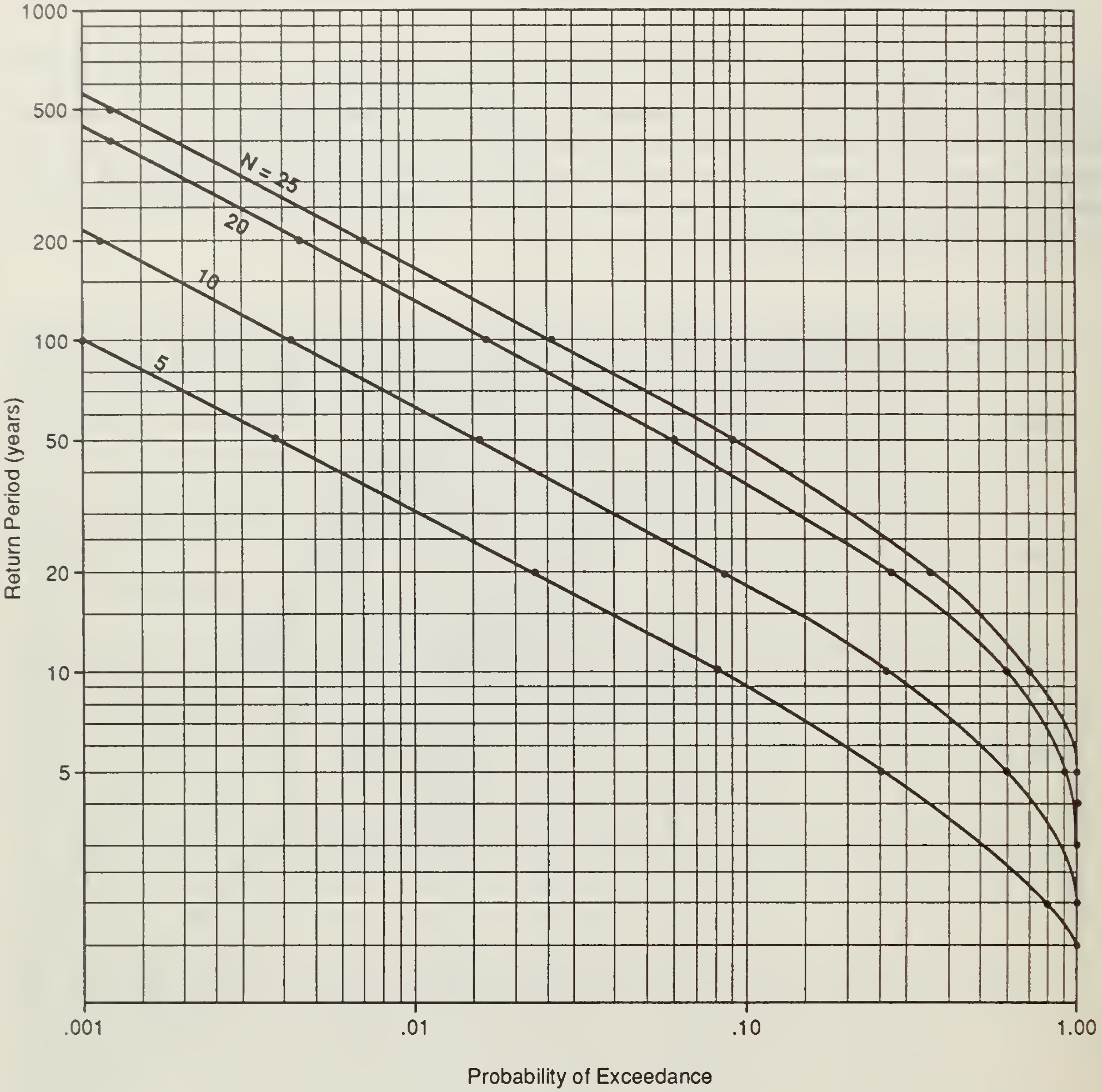

Figure 3. Return Periods Corresponding to the Probability of Experiencing Two or More Events Equal to or Greater than the T-Year Event in N Years.

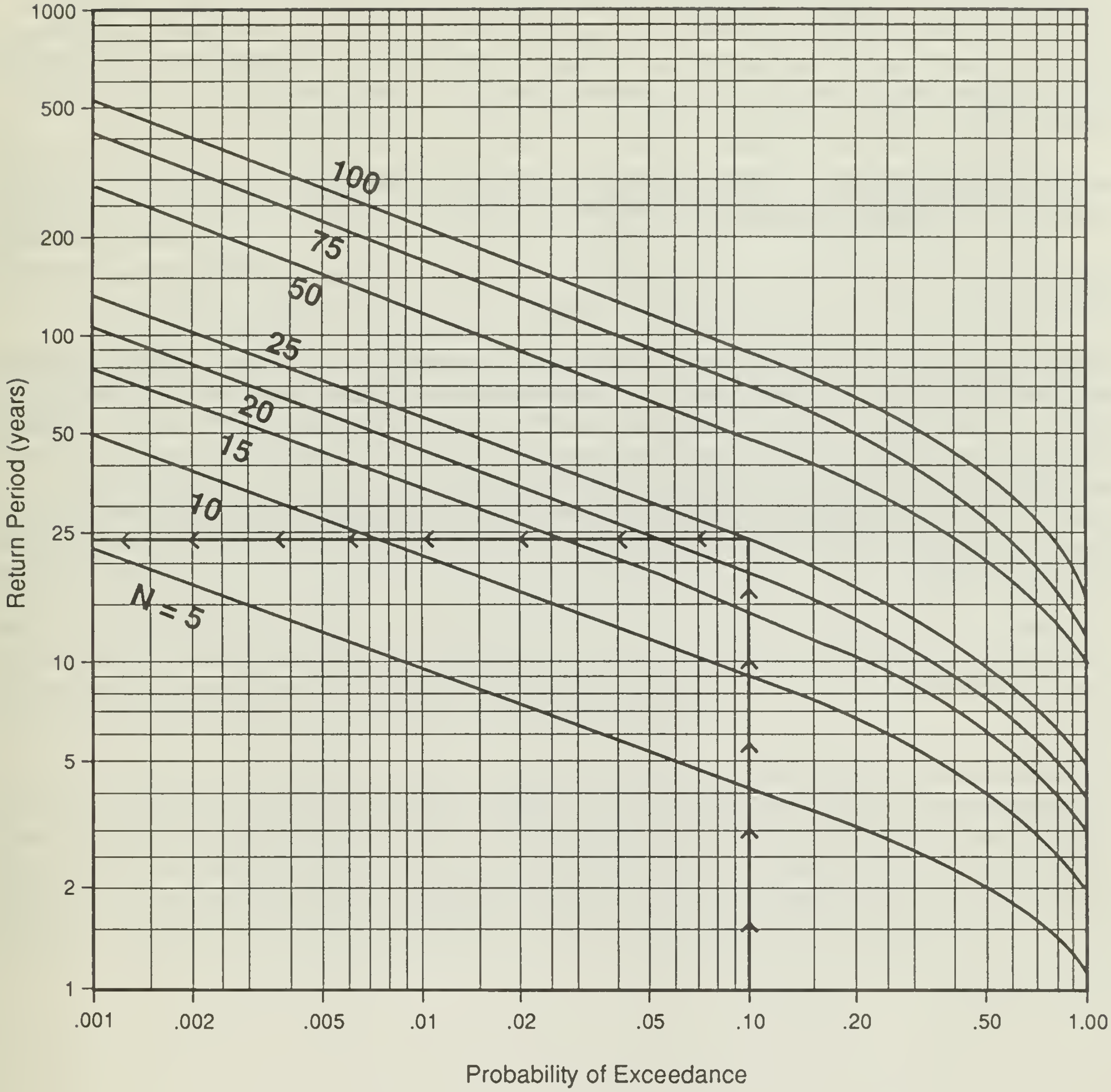

Figure 4. Return Periods Corresponding to the Probability of Experiencing Three or More Events Equal to or Greater than the T-Year Event in N Years.

Example Problem 1: A BLM district engineer has been asked to design and build a bridge suitable for use by logging trucks. The bridge will be designed to have a physical and economic life of 5 years, which is the duration of the associated timber sale contract. Failure of the bridge would not mean a great economic loss, but the associated channel damage and sediment problems created by a bridge failure would impact a critical downstream trout habitat. Because of the environmental hazards, the District Manager has decided on a risk level of 5 percent.

The hydrologist has been asked to provide a design Q for the project. Using Figure 2, he determines that the return period of the design event should be 100 years ($p = .01$).

The probability relationships given in this Technical Note are not restricted to flood frequency analyses. The following example relates to a low-flow problem incurred in a fish habitat improvement project.

Example Problem 2: A BLM hydrologist has been asked by his boss to assist in the hydrologic design of a fishery habitat improvement project. Specifically, he must design a spawning channel that will allow the spawners to easily migrate upstream, even in low flows. The project life has been set at 25 years. The fishery biologist feels that a risk level of 10 percent is reasonable for the project. Furthermore, he does not feel that the population would be damaged irretrievably if the channel failed to do its job twice within the 25-year period. By referring to Figure 4 the hydrologist can read directly the probability of experiencing three or more events equal to or greater than the T-year event. From Figure 4, the return period is 22.2 years, or a probability of .045.

HYDROLOGIC FREQUENCY ANALYSIS

Once a return period is determined, the specialist must then calculate the event magnitude corresponding to that return period.

The magnitude of a selected event, such as the 25-year flood flow from a watershed, is taken directly from a frequency curve. Frequency curves for extreme events, such as floods and low flows, can be developed from raw data plots on log-probability graph paper or from an appropriate frequency analysis such as log-Pearson Type III (USDI, 1982). Frequency curves for ungauged watersheds may be obtained from regional relationships or from a hydrologic model, such as the SCS Runoff Curve Number Method (Van Haveren and Jackson, 1988).

To account for the uncertainty element of hydrologic risk, the data set should first be checked and adjusted for nonhomogeneity or inconsistencies. All events used in the frequency analysis should be random and independent. If the record is made up of mixed populations, e.g., flood peaks created by different types of hydrologic events (snowmelt, rainstorms, rain-on-snow), special treatment of data is indicated.

An example of a flood frequency curve is shown in Figure 5. This annual flood series is from Bear Creek near Morrison, Colorado, a streamflow station that exhibits the mixed population phenomenon. The log-Pearson Type III curve has been fitted to the entire population of annual flood peaks but does not adequately model the floods above 4,000 cubic feet per second (cfs). An analysis of the station record showed that all the events over 4,000 cfs were derived from summer rainstorms. The floods derived from summer thunderstorms appear to have a distribution distinct and separate from the floods derived primarily from snowmelt. This is an example of a data set in which separate frequency distributions could be fitted to the observed flood peaks—one for snowmelt-derived peaks and one for summer thunderstorm-derived peaks. A good reference for general hydrologic frequency analysis is Kite (1976).

Once a frequency distribution has been chosen and data fitted to this distribution, confidence limits should be computed for the frequency curve as explained in USDI (1982). The confidence level should be set by the hydrologist in accordance with the way he or she feels about the original data set. A confidence level of 95 percent is commonly used for most applications but is not a hard-and-fast rule. The upper confidence limit value then becomes the recommended design event for the project. For the Bear Creek data in Figure 5, 95-percent confidence limits have been estimated for the log-Pearson Type III flood frequency curve.

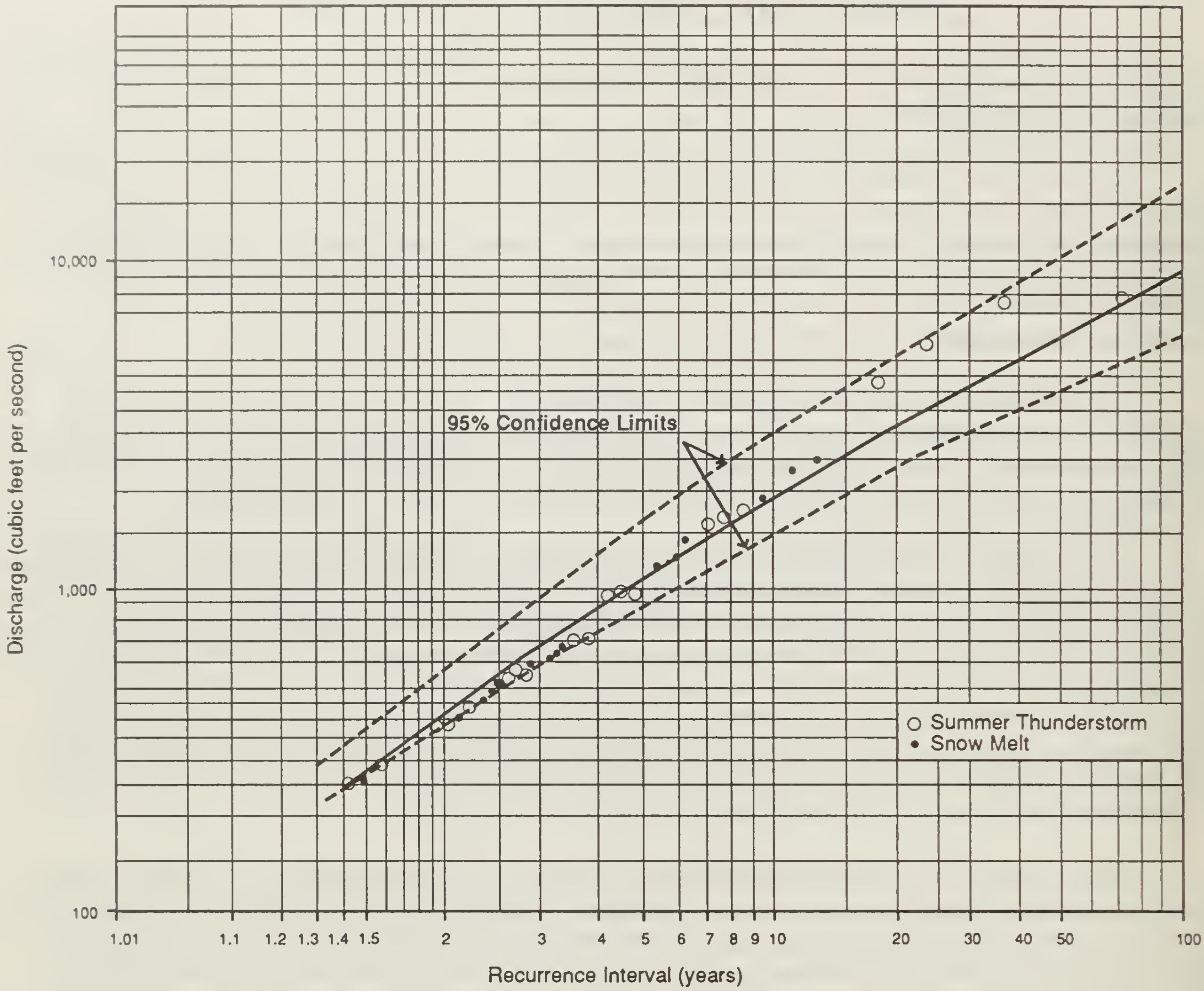

Figure 5. Flood Frequency Curve for Bear Creek above Morrison, Colorado (Drainage Area = 165 sq. mi.; USGS Sta 06710500). The fitted curve is from a log-Pearson Type III frequency distribution fitted to 66 years of annual flood peaks (1920-1985).

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